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A STUDY OF ACOUSTIC NAVIGATION IN DEEP WATER.(U)
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U. S. NAVY UNDERWATER SOUND LABORATORY
FORT TRUMBULL, NEW LONDON, CONNECTICUT

A STUDY OF ACOUSTIC NAVIGATION IN DEEP WATER

by

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INTRODUCTION

Since 1961, the geographical area south of Bermuda has been utilized as a range for conducting tests designed to study general problems in acoustic research. The installation of the ARTEMIS Receiver Field, FISHBOWL Array, and the TRIDENT Vertical and Horizontal Strings have provided the U. S. Navy Underwater Sound Laboratory Research Detachment, located at Tudor Hill, Bermuda, with a large number of deep water receivers that are cabled to the Laboratory for the purposes of conducting such research.

This area has therefore been the host to frequent Naval and oceanographic ships conducting various experiments. Such studies of acoustic propagation and sonar equipment valuation always require an accurate knowledge of the ship's position and have encouraged attempts by personnel at the Research Detachment to utilize this existing complex of deep water receivers as an acoustic navigation system.

RECEIVER GEOMETRY

The complex of hydrophones that are cabled to Tudor Hill can be see in Figure 1. This figure represents a three dimensional drawing of the ocean south of Bermuda. The two rises in the upper left hand side of the figure represent Challenger and Plantagenet Banks. The ARTEMIS Receiver Field, consisting of 210 modules, lies on the rise of Plantagenet Bank. Twenty-six miles to the east, at a depth of approximately 12,600 feet, the FISHBOWL Array with 80 line hydrophones is shown. South of

FISHBOWL, at a distance of 15 nautical miles, the TRIDENT Vertical Array of 40 suspended receivers is situated, and below that, the TRIDENT Coherence String of six hydrophones on a cable that runs diagonally across toward the southeast such that its deepest hydrophone C-1 is approximately 32 nautical miles south of FISHBOWL.

A study of acoustical navigation using the receivers C-1, V-1, a FISHBOWL hydrophone, and 4-21-R from ARTEMIS has been carried out. As indicated in the figure, these receivers roughly outline an "L" shaped configuration 26 by 32 miles long. This arrangement is certainly not optimum but adequate for many areas of investigation.

POSITIONING TECHNIQUES

Prior to the navigation study that will be reported here, experimenters from the Bell Telephone Laboratories had utilized an acoustic positioning system based on the graphical plotting of time difference lines in a small area around the TRIDENT Vertical Array. This system requires personnel on the ship putting a charge of some sort in the water and personnel at the Bermuda Research Detachment recording time differences of the arrival times at the various units and determining position from a pre-drawn graph of time difference lines. This method, however, loses accuracy at ranges more than 30 kyds from TVA and does not cover areas much beyond this. Use of Loran C has been satisfactory; however, it may fail completely at night due to sky wave interference, and not all ships have such operational equipment available. The study presented here includes time difference curves for a larger area of interest to the experimenter. Two related methods can be used to acoustically position a ship. The first, as mentioned above, is an extension of the present time difference technique to ranges up to 150 kiloyards. The second requires the use of a radio link and is based upon the absolute travel time from the ship to the receiver. Using either method, the signals are received at the various hydrophones, amplified, fed through a band pass filter centered around 300 Hz and then presented on any suitable recorder equipped with an accurate time signal.

The incoming signals from the detonated charge can then be read from the recorder and the time difference between arrivals at two hydrophones can be determined quite accurately. Acoustic positioning by means of direct travel time is very similar except that now a radio link from the ship in the area to the Tudor Hill Laboratory is also fed into the optical recorder. When the charge goes off close to the ship, the explosion is received on a suspended hydrophone which in turn triggers a transmitted pulse from the ship's radio to the Bermuda Laboratory. By counting the elapsed time from the radio pulse to the reception on the

various hydrophones, it is possible to draw arcs on a chart and position the ship. The corresponding conversion from time to range is derived from a ray tracing program calculated on a computer. Here, the readout consists of travel time versus range for signals from a source 30 feet deep to various selected depths of the receivers. In doing this program it was assumed that the depth of water was uniformly 15,000 feet. This is not exactly true for the area we are concerned with, especially in the area of ARTEMIS because of the Plantagenet rise. However, studies have shown that the effects in general on travel time are negligible.

Figure 2 is a portion of the ray tracing showing range and travel time output plotted for the shallowest 4-21-R (4200 feet) and deepest (C-1) (14,709 feet) units. The discontinuities in the plots are the major problem involved in the use of this long range acoustic navigation system; therefore, a discussion of their cause and effects is primary. In Figure 2 a discontinuity is observed at a range of 25 kyds for 4-21-R and 30 kyds for C-1.

The jumps or discontinuities occur in the output of the program because ray theory requires that certain rays will or will not reach a certain point depending upon angle of departure, velocity gradient, and water depth. What has happened to cause these jumps is that the program allows signals to be received via the direct path out to a certain range from the source. Beyond this, no direct pulse is theoretically possible and the first pulse received is the bottom-surface reflected. There is a distinct time difference between these various modes at all ranges so that the travel time curve has a discontinuity at those ranges where theory predicts a propagation path change. Physically, this change is not quite as abrupt in range and an observer must decide which path the first received pulse followed. Both TRIDENT Receivers, V-1 and C-1, have discontinuities at ranges of 30 kyds and again at 95 kyds from each receiver since all lie more or less at the same depth. The ARTEMIS receiver 4-21-R being considerably shallower has discontinuities at 25, 70 and 105 kyds.

The implications of these discontinuities to any acoustic navigation system is that ambiguities in position are caused at certain discrete ranges from the respective units. A top view of the area south of Bermuda and the receivers used in this positioning system can be seen in Figure 3 which shows the receivers and the corresponding arcs representing the ranges at which the discontinuities fall.

High positioning error is to be expected from areas where two or more discontinuities overlay. One such region can be seen at ranges close to 95 kyds on a bearing of 195° from the TVA. In other places where only one receiver is effected, its measured travel time or time

difference can be discarded in favor of a more reliable measurement obtained from other units. One can easily eliminate such high error regions by either changing the receiving configuration or adding more receivers remote to the existing areas. As either of these alternations were not physically possible to us, the existing network was employed.

If one were to employ a positioning system using absolute travel time from ship to receiver, i.e., with a radio link to the Laboratory at Bermuda, a set of circular arcs representing constant travel time could be drawn for any receiver, and the ship's position obtained by graphical methods, However, the use of charts, although quite adequate for general use, are subject to drawing error which at times may be considerable. Analytical calculations of the ship's position can similarily be made by calculating the range from the travel time as predicted by the ray paths, and combining it with the known positions and geometry of the receivers. Navigation could then be accomplished rapidly with any computer programmed for the particular problem.

THEORETICAL ERRORS

In an attempt to find the error that might be expected in such a position, an error analysis has been carried out using a set of equations derived from direct travel time vs. range plots. Assuming that an error of 30 ms exists in reading the travel time with the receiving system consisting of the 3 receivers, 4-21-R, V-1 and C-1, 40 ms due to distance of shot from ship, and 30 ms to cover transmitter keying time, a total 100 ms error in reading exact travel time is suffered. Experience with such systems has indicated that such errors are reasonable, and the latter two can be estimated and compensated for in calculations. Using these figures a plot of error as a function of range from TVA, at a bearing of 225°, has been done and this is shown in Figure 4. The bearing is a fairly good one for the geometry employed and the plot shows that excellent accuracy can result from this method, especially if more than two units are used. The plot shows the largest error at any range and can be considered accurate except for the discontinuity errors at the discrete ranges which are neglected.

In drawing the curve on Figure 4, the travel time to range conversion is accomplished from a set of linear equations of the form $T = AR + B$ fitted to a plot of travel time vs. range where both an A and B are particular constants that apply to a region free of discontinuities with T and R being time and range. These equations are listed in Table 1. The incremental time errors that are assumed are then converted to ranges leading to a two dimensional area of ambiguity. Figure 4 essentially shows the largest side of this area as a function of range.

A similar analysis can be performed with a navigation system that employs only time difference of arrival, however, here a solution becomes more difficult. In order to obtain a position from three measurable time differences, a large number of simultaneous equations must be solved. Most of the positioning that has been done using this technique has been accomplished graphically from charts where time difference lines are drawn over certain geographical areas as has been done in the area around the TRIDENT Vertical Array.

Figure 5 shows such a section of a graphical chart of time difference lines out at the range of 120 kyds from the TRIDENT Vertical Array to the southwest along the bearing 225°. The time differences shown are those between the ARTEMIS unit and C-1 and that between FISHBOWL and C-1.

Here the effect of the discontinuities in the range and travel time curves can be seen. Drawing error in making such a chart will be a major cause of error as the points on each constant time difference curve are simply intersections of two absolute travel time curves. In addition errors will result where time difference lines cross at a shallow angle. The latter is especially a problem where the travel time circles are tangential. Again, an analytic treatment using the equations would eliminate much of this error, but on line computations for rapid positioning are impossible without a computer. With such a computer the travel time vs. range equations, combined with some elementary trigonometry, provide a set of equations that can determine range and bearing from any reference point such as the TVA.

An error analysis for ranges at bearing 225° has been done using the equations of time difference and can be seen in Figure 6. The assumed errors here were 50 ms in reading each time difference and 50 ms as an arrival error. This leads to a total of 150 ms which is generally rather pessimistic. The error vs. range is plotted in Figure 6 for time differences, V1 - C1 and ARTEMIS C1. Here the error increases seriously at long ranges, since the errors increase their effect as plots of time difference curves become nearly tangential. Addition of another time difference curve, TRIDENT Vertical Array to ARTEMIS would reduce this error slightly.

Here, as before, the calculated error does not include errors arising from the discontinuities in the travel time versus range curves. Physically, such discontinuities result in multipath arrivals to the various receivers in direct positioning, or receiver pairs when using time difference. These are observed to follow a gradual transmission from one set of arrival differences to another.

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EXPERIMENTAL RESULTS

Attempts have been made to verify the above at sea. The intention was to find good Loran C fixes and compare these with acoustic fixes by both time difference and travel time methods done simultaneously. Unfortunately, this has yet to be done successfully, although tried twice. Generally, the Loran C was inoperative or its positions in doubt. Thus, no real verification of the methods have been made. However, the discontinuities have been seen near the predicted ranges and agreement, both internally for each method using different groups and between the two methods is within the two kiloyards predicted by the error analyses. Now both methods have been shown to be easily performed with a minimum of difficulties or mistakes. A hand granade has been shown to consistantly show up on all units, regardless of range.

Some problems which have been encountered are the leakage paths up Plantagenet Bank which leads to a precurser pulses on ARTEMIS and a gradual shifting of discontinuities from five to ten kiloyards respectfully from winter to summer conditions. Several areas where certain arrivals are weaker have also caused problems in picking the correct time.

Curves of time difference based upon the above method have been drawn up for use at the Bermuda Research Detachment. It is hoped that through the use of these curves a better idea of the accuracy and uses of this system may be gained. The use of the computer at the Detachment to calculate positions using the equations will be undertaken soon. This will hopefully give a dependable, accurate system for the conduction of experiments in this critical area.

CONCLUSION

The studies carried on in finding an acoustic positioning system, outlined above, have proven that such a system is not only valid for the areas which we are interested in, but also have shown that such a system is accurate. This is especially true if absolute travel time from source to each receiver can be determined. Accuracies of 2 kyds at a range of 150 kyds can be expected in most areas. This system should be a good backup for those cases where Loran is operating and should provide the necessary information when Loran C is lacking or inoperable.

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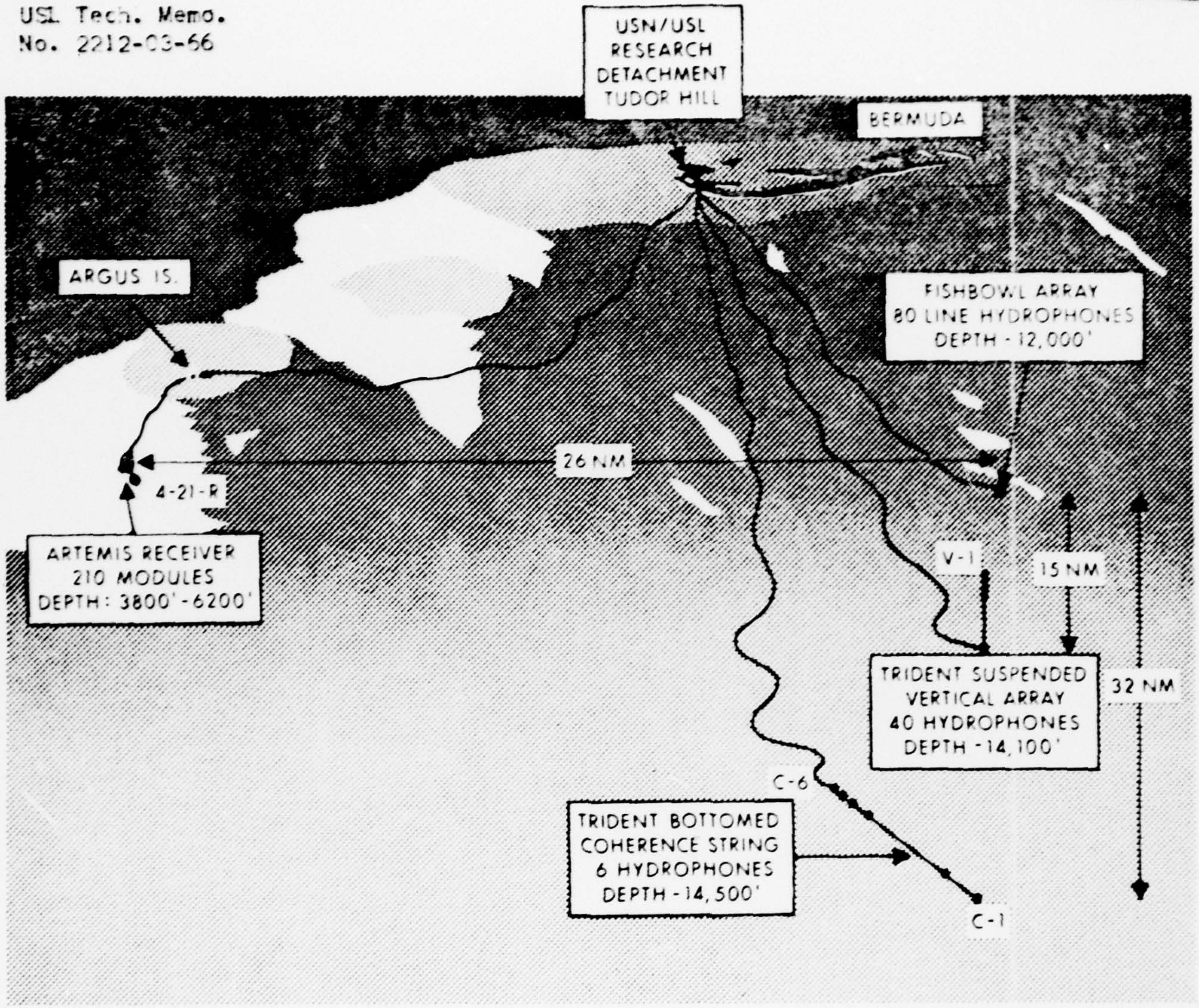

HYDROPHONE CONFIGURATION

FIGURE 1

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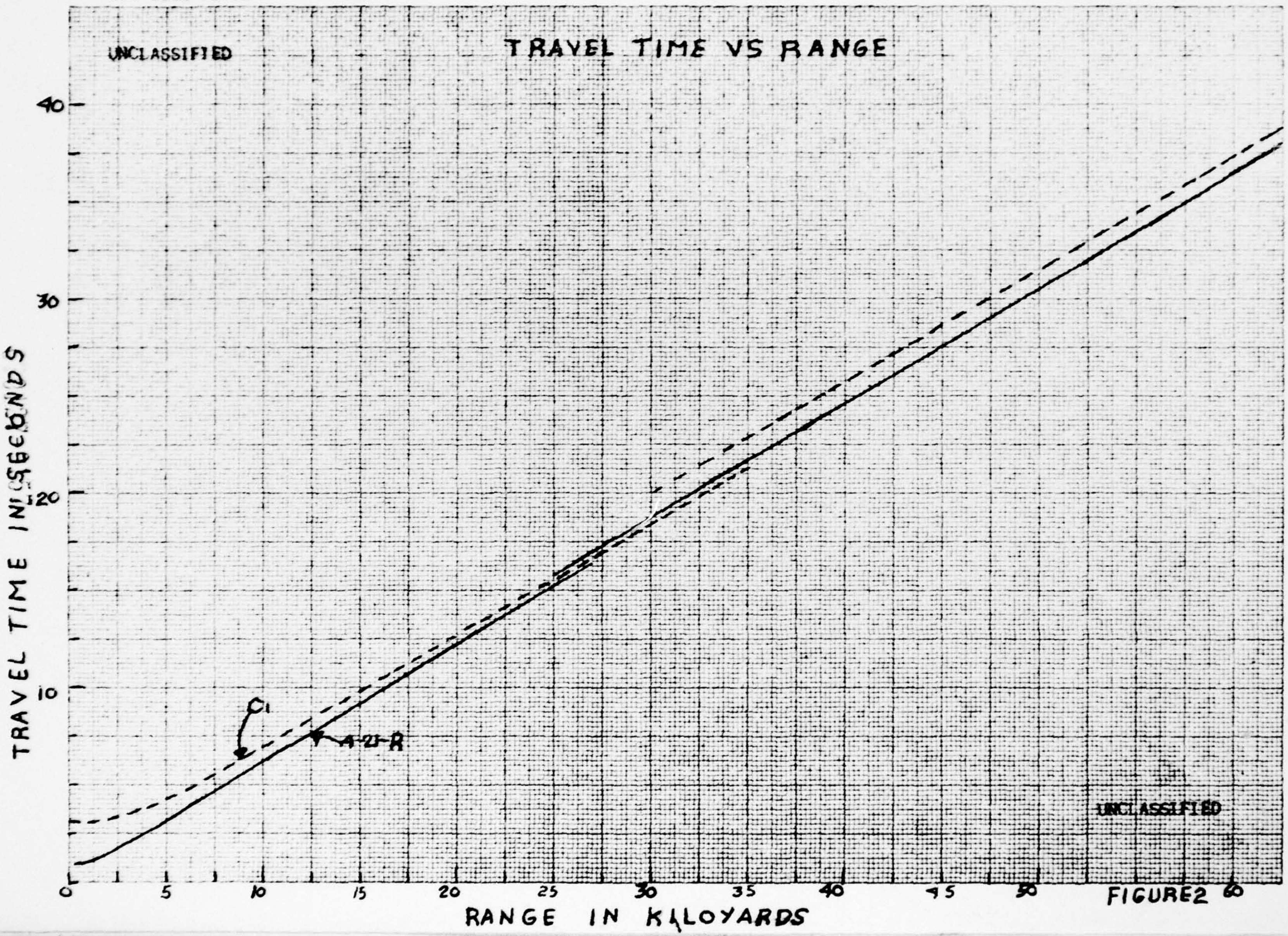

FIGURE 2

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ARCS SHOWING REGIONS OF DISCONTINUITIES

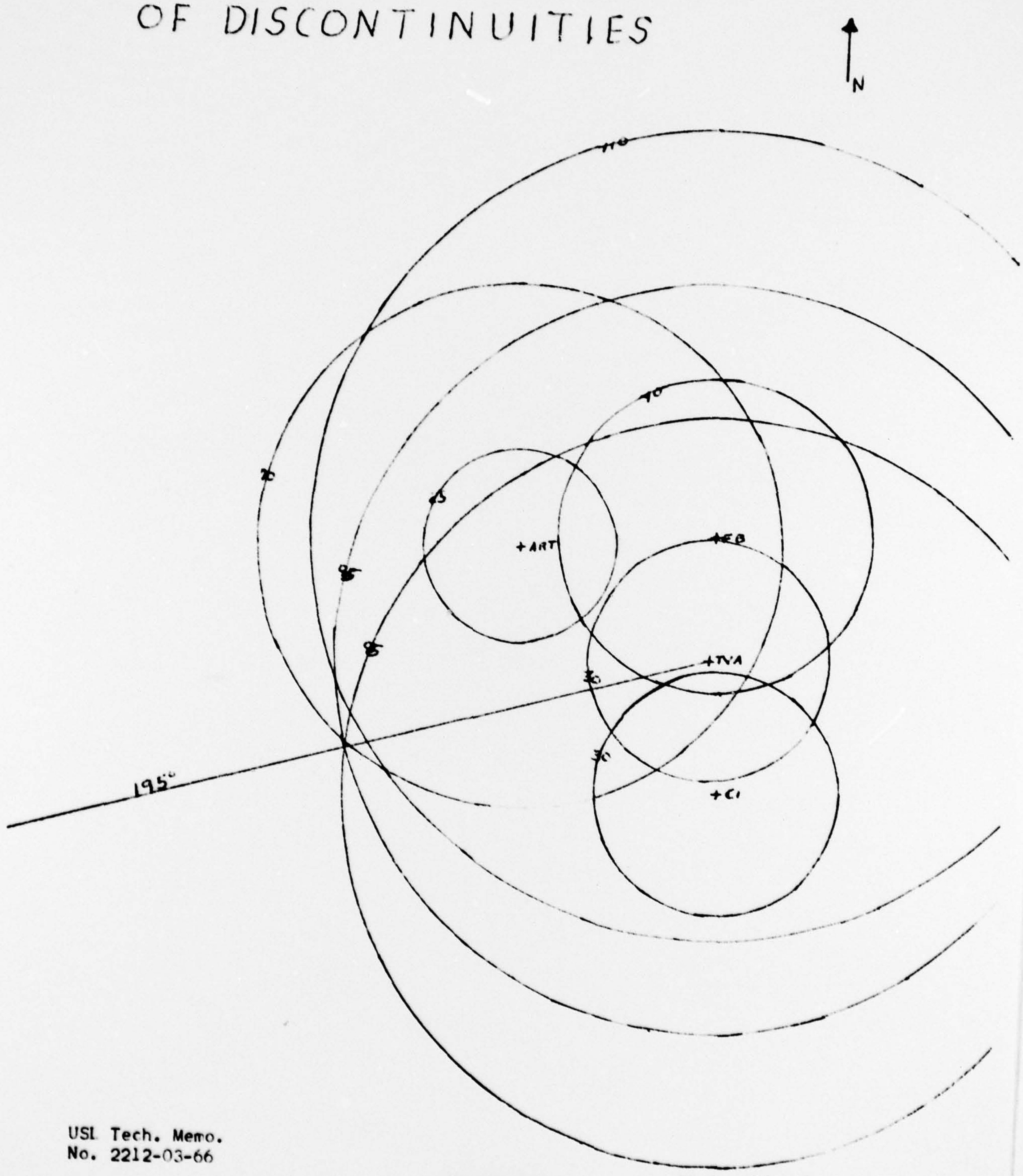

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FIGURE 3

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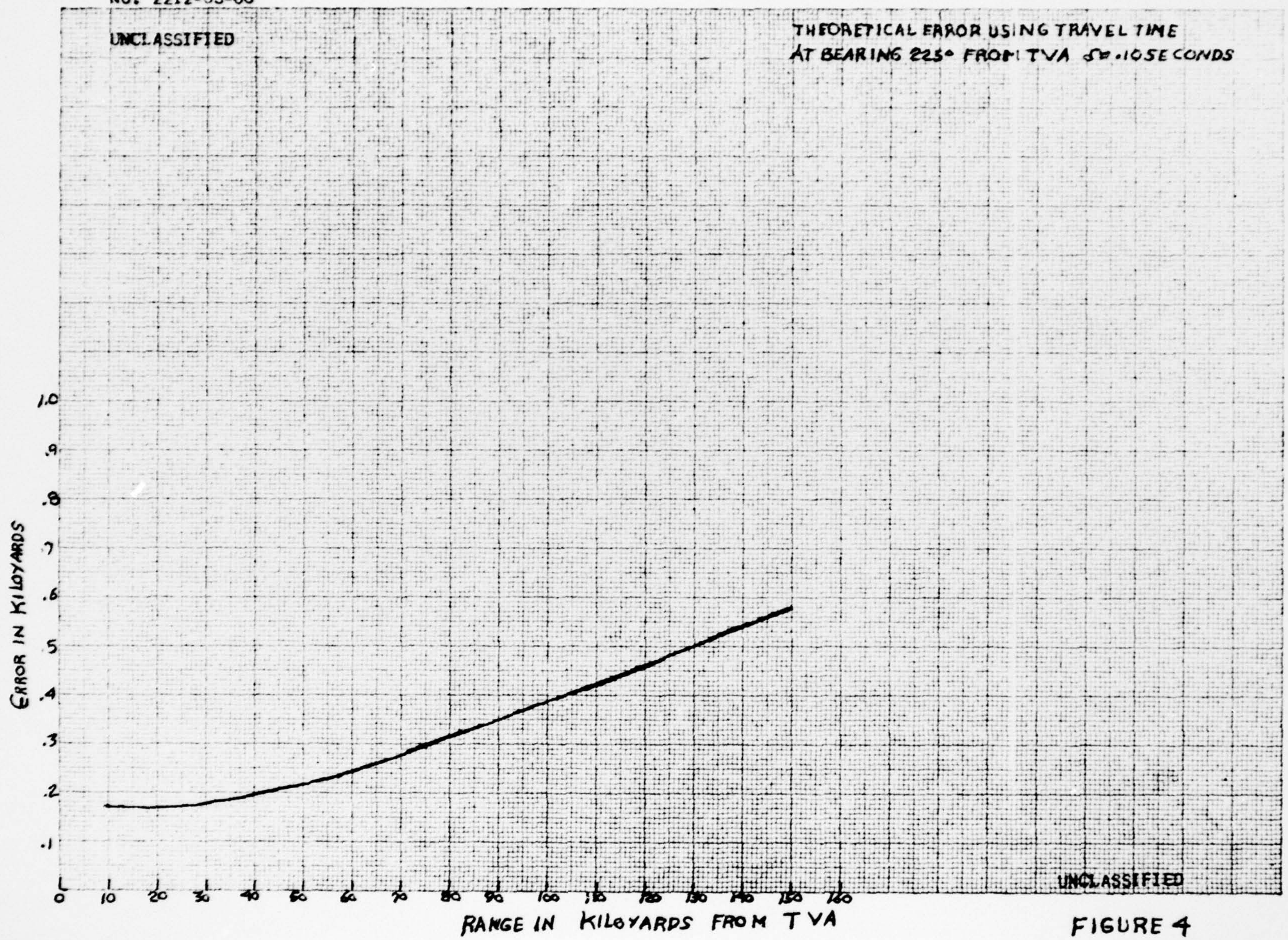

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FIGURE 4

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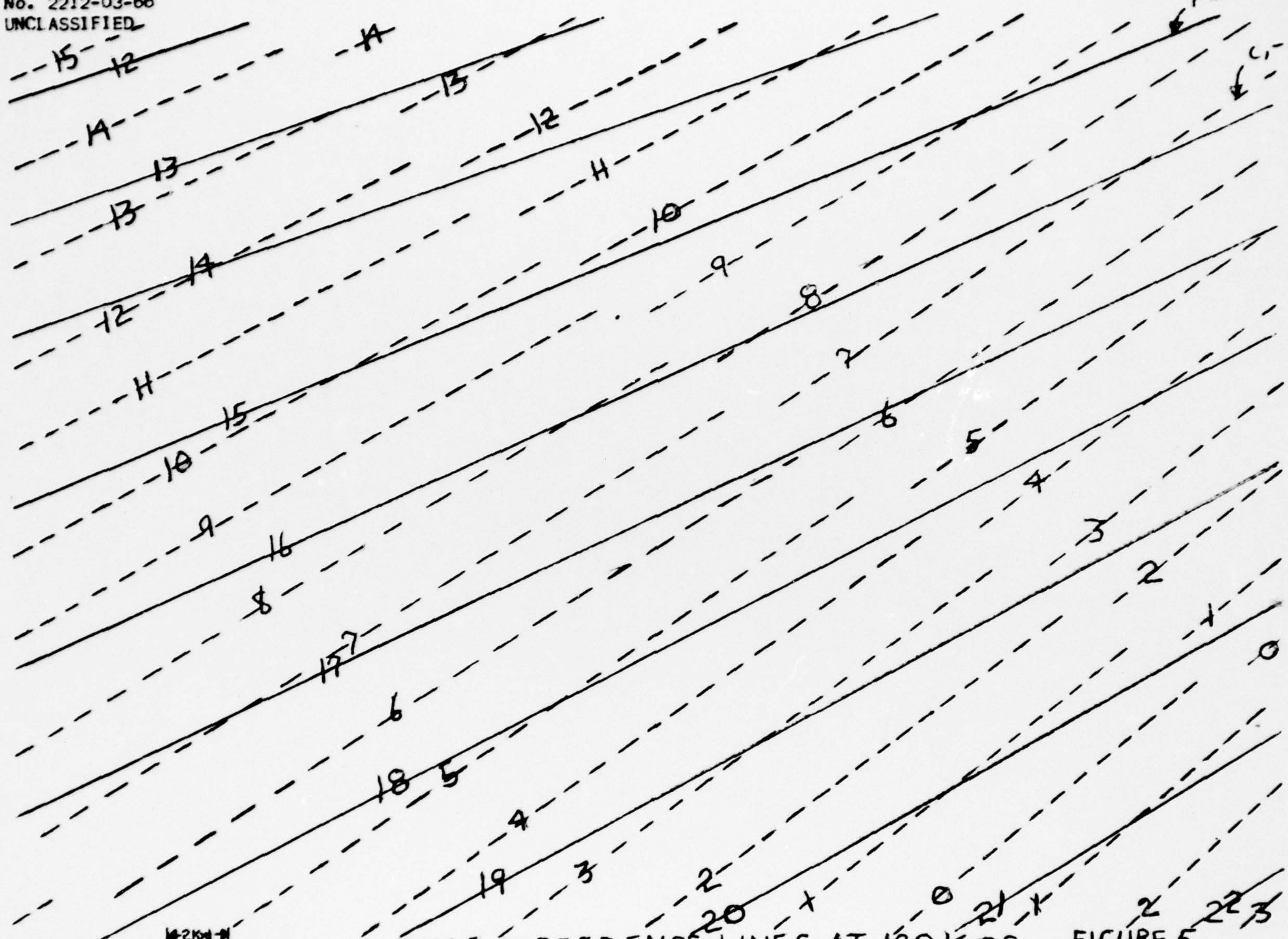

TIME DIFFERENCE LINES AT 120 KYDS

FIGURE 5
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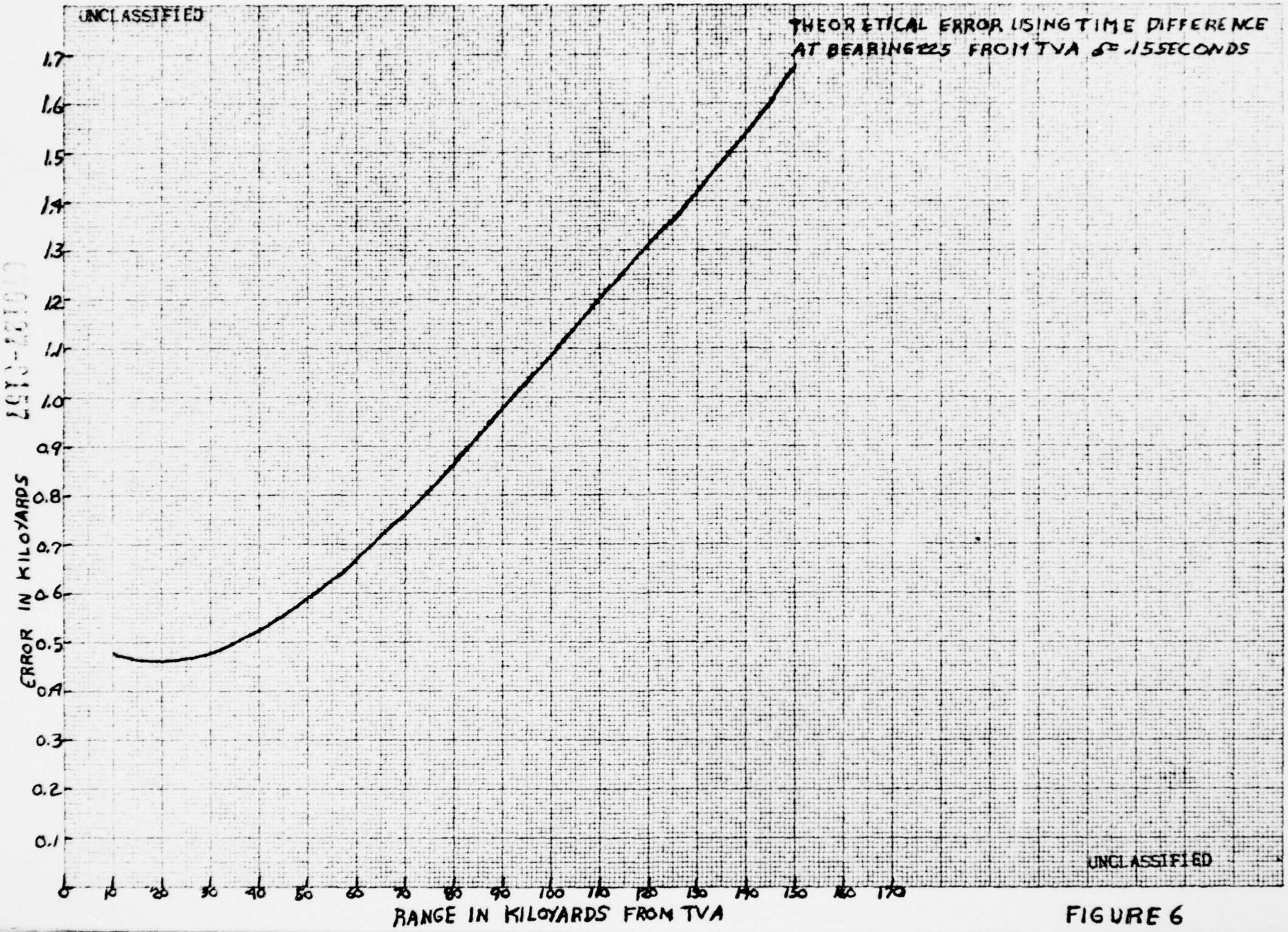

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FIGURE 6

TABLE 1

VERTICAL

RANGE Kyds.	
10 – 30	$t_1 = 0.583 R_1 + 0.785$
30 – 95	$t_1 = 0.582 R_1 + 2.54$
95 – 150	$t_1 = 0.588 R_1 + 3.60$

ARTEMIS

RANGE Kyds	
10 – 25	$t_2 = 0.598 R_2 + 0.31$
25 – 70	$t_2 = 0.588 R_2 + 1.22$
70 – 105	$t_2 = 0.597 R_2 + 1.19$
105 – 130	$t_2 = 0.597 R_2 + 1.64$
130 – 150	$t_2 = 0.580 R_2 + 4.00$

FISHBOWL

RANGE Kyds	
10 – 40	$t_3 = 0.590 R_3 + 0.700$
40 – 110	$t_3 = 0.592 R_3 + 1.80$
110 – 150	$t_3 = 0.587 R_3 + 3.60$

COHERENCE

RANGE Kyds	
10 – 30	$t_4 = 0.579 R_4 + 0.920$
30 – 95	$t_4 = 0.583 R_4 + 2.50$
95 – 150	$t_4 = 0.587 R_4 + 3.49$